INFLUENCE OF BEHAVIOUR FACTOR ON SEISMIC DESIGN AND PERFORMANCE OF REINFORCED CONCRETE MOMENT RESISTING FRAME IN MALAYSIA

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LIST OF ABBREVIATIONS

CP	Collapse prevention
DCH	Ductility class high
DCL	Ductility class low
DCM	Ductility class medium
FFE	Far field earthquake
IDR	Interstorey drift ratio
IDR_{mean}	Mean interstorey drift ratio
IO	Immediate occupancy
K_e	Secant or effective stiffness
$K_{elastic}$	Elastic stiffness
LS	Life safety
LVDT	Linear variables displacement transducer
MDOF	Multi degree of freedom
MMD	Malaysia meteorological department
NFE	Near field earthquake
NTHA	Nonlinear time history analysis
PEER	Pacific Earthquake Research Center
PGA	Peak ground acceleration
RC	Reinforced concrete
SDOF	Single degree of freedom

LIST OF SYMBOLS

Δ_u	Ultimate displacement
Δ_y	Yield displacement
μ_φ	Curvature ductility factor
a_g	Design ground acceleration on type A ground
a_{gR}	Reference peak ground acceleration
As_{prov}	Total area of steel provided
As_{req}	Total area of steel required
A_{sw}/s_{prov}	Total area of steel provided for shear and its spacing of bar
A_{sw}/s_{req}	Total area of steel required for shear and its spacing of bar
A_{swx}	Total area of confinement reinforcement provided along x direction
A_{swy}	Total area of confinement reinforcement provided along y direction
b_0	Width of column confined core
b_c	Column gross cross-sectional width
b_i	Distance between consecutive engaged bars
d_{bL}	Diameter of longitudinal bar
d_{bw}	Diameter of shear or confinement bar
E	Earthquake load
F_b	Base shear force
f_{cd}	Design value of concrete compressive strength
f_{ck}	Characteristic cylinder strength of concrete
f_{ctm}	Mean value of tensile strength of concrete
F_i	Lateral load on storey i
F_u	Ultimate load

f_y	Yield strength of reinforcement
f_{yd}	Design value of yield strength of steel
f_{ywd}	Design yield strength of the shear reinforcement
g	Acceleration due to gravity, m/s^2
G_k	Dead load
H	Storey height
h_0	Depth of column confined core
h_c	Width of the column
h_w	Depth of beam
k_D	Factor reflecting the ductility class
M	Bending moment
m	mass of structure
M_{Rb}	Design moment resistance of beam
M_{Rc}	Design moment resistance of column
$\mathrm{M_w}$	Magnitude of earthquake intensity
N	Number of storey
P	Axial load of column
q	Behaviour factor
Q_k	Live load
R	Strength reduction factor
S	Soil factor
s	Spacing of bar
$S_d(T_1)$	Ordinate of the design spectrum at period T_1
s_{max}	Maximum spacing of bar
T_1	Fundamental period of vibration

T_B	Lower limit of the period of the constant spectral acceleration branch
T_C	Upper limit of the period of the constant spectral acceleration branch
T_D	Beginning of the constant displacement response range of the spectrum
V	Shear force
v_d	Normalised design axial force in column
γ_I	Importance factor
γ_{Rd}	Model uncertainty factor on the design value of resistance
$\varepsilon_{sy.d}$	Design value of tension steel strain at yield
λ	Correction factor
μ	Ductility
ρ	Reinforcement ratio in the tension zone
ρ'	Reinforcement ratio in the compression zone
ρ_{max}	Maximum reinforcement ratio
ρ_{min}	Minimum reinforcement ratio
$\Psi_{E,i}$	Combination coefficient for variable action
$\omega_{wd\ prov}$	Mechanical volumetric ratio of confining hoops provided
$\omega_{wd\ req}$	Mechanical volumetric ratio of confining hoops required

PENGARUH FAKTOR KELAKUAN KE ATAS REKABENTUK SEISMIK DAN PRESTASI KERANGKA MOMEN KONKRIT BERTETULANG DI MALAYSIA

ABSTRAK

Gempa bumi sederhana yang terjadi pada 5 Jun 2015 di Ranau, Sabah, dengan magnitude 5.9 telah menyebabkan kerosakan pada bangunan-bangunan. Dengan itu, adalah penting untuk mempertimbangkan rekabentuk seismik untuk bangunan-bangunan baru di wilayah tersebut. Dalam rekabentuk seismik, suatu konsep yang dinamakan sebagai faktor kelakuan yang berkait rapat dengan kemuluran telah dicadangkan. Baru-baru ini terdapat komen dan cadangan bahawa nilai faktor kelakuan sekarang patut diganti. Dengan itu, adalah penting untuk mengkaji kesan perubahan nilai faktor kelakuan dari dua perspektif iaitu reka bentuk dan prestasi. Selain itu, aturan histeresis mewakili kelakuan struktur apabila dikenakan beban kitaran sisi seperti gempa bumi. Kesesuaian sesuatu aturan histeresis untuk digunakan dalam program komputer bagi analisis sejarah masa tidak linear perlu diperiksa. Di wilayah seismik tinggi, kejadian gempa bumi berulang tidak boleh diabaikan dalam analisis struktur kerana ia mencetuskan kerosakan yang lebih besar ke atas sistem struktur. Dengan itu, pengaruh gempa bumi berulang di wilayah seismik medium di Malaysia juga perlu disiasat. Tesis ini membentangkan pengaruh faktor kelakuan ke atas rekabentuk seismik bagi bangunan kerangka penahan momen konkrit bertetulang di Malaysia. Rekabentuk seismik telah dijalankan untuk kemuluran kelas pertengahan dengan faktor kelakuan dari 2.3 hingga 5.5 merujuk kepada Eurocode 8. Ujian beban kitaran sisi juga telah dijalankan untuk mengkaji kelakuan struktur apabila dikenakan

beban sisi. Ia juga penting untuk memeriksa kesesuaian *Modified Takeda Degrading Stiffness* sebagai aturan histeresis bagi analisis sejarah masa tidak linear. Akhir sekali, prestasi struktur bagi semua kerangka yang telah direkabentuk dinilai dengan analisis sejarah masa tidak linear dengan mempertimbangkan gempa-gempa tunggal dan berulang. Kajian ini menyumbang kepada penilaian terhadap nilai faktor kelakuan berdasarkan rekabentuk dan prestasi struktur. Selain itu, kajian ini juga memeriksa kesesuaian *Modified Takeda Degrading Stiffness* sebagai aturan histeresis. Sebagai kesimpulan, nilai faktor kelakuan sangat mempengaruhi rekabentuk seismik. Jumlah berat besi pengukuhan boleh dikurangkan sehingga 36.2% dengan menggunakan faktor kelakuan tinggi dalam rekabentuk. Daripada ujian beban kitaran sisi, boleh disimpulkan bahawa *Modified Takeda Degrading Stiffness* sesuai untuk digunakan sebagai aturan histeresis dalam analisis sejarah masa tidak linear. Nilai kekakuan nyahbeban, α adalah bersamaan 0.1 sementara nilai kekakuan pembebanan semula, β adalah bersamaan 0.4. Berdasarkan penilaian ke atas prestasi struktur, magnitud maksimum bagi anjakan antara tingkat disebabkan oleh gempa bumi berulang mencapai sehingga 30.1% hingga 40.6% lebih tinggi daripada gempa bumi tunggal. Dengan itu, faktor kelakuan dari 2.3 hingga 5.5 adalah diterima untuk digunakan bagi rekabentuk seismik bangunan kerangka penahan momen konkrit bertetulang baru di atas tanah jenis B di wilayah seismik pertengahan di Malaysia. Di atas tanah jenis D, faktor kelakuan dihadkan dari 2.3 hingga 4.54.

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ABSTRACT

A moderate earthquake which occurred on 5th June 2015 in Ranau, Sabah, with M_w5.9 had caused damages on buildings. Therefore, it is important to consider seismic design for new buildings in that region. In seismic design, a concept namely as behaviour factor, *q* which strongly relates with ductility was proposed. Recently, there are comments and suggestion that the current value of behaviour factor, *q* shall be replaced. Therefore, it is importance to study the effect of changing the value of behaviour factor, *q* from two different perspectives which is design and performance. Besides, hysteresis rule represents the structural behaviour when subjected to cyclic lateral load like earthquake. The suitability of a hysteresis rule to be used in computer program for nonlinear time history analysis has to be checked. In high seismic region, the occurrence of repeated earthquake cannot be neglected in structural analysis since it induces greater damage on structural system. Therefore, the influence of repeated earthquake in medium seismic region in Malaysia also has to be investigated. This thesis presents the influence of behaviour factor, *q* on seismic design for reinforced concrete moment resisting frame buildings in Malaysia. The seismic design had been conducted for ductility class medium with behaviour factor, *q* from 2.3 to 5.5 by referring to Eurocode 8. The cyclic loading test also had been conducted to investigate the structural behaviour when subjected to lateral load. It is also important to check to suitability of Modified Takeda Degrading Stiffness as hysteresis rule for nonlinear

time history analysis. Finally, the structural performance of all designed frames had been evaluated by using nonlinear time history analysis considering single and repeated earthquakes. This study contributes to the evaluation on the value of behaviour factor, q based on design and structural performance. Beside, this study also checked the suitability of Modified Takeda Degrading Stiffness as hysteresis rule. As a conclusion, the value of behaviour factor, q is strongly influencing the seismic design. The total weight of steel reinforcement can be reduced up to 36.2% by using higher behaviour factor, q in design. From cyclic loading test, it can be concluded that the Modified Takeda Degrading Stiffness is suitable to be used as hysteresis rule in nonlinear time history analysis. The value of unloading stiffness, α is equal to 0.1 while the value of reloading stiffness, β is equal to 0.4. Based on evaluation on structural performance, the magnitude of maximum interstorey drift ratio caused by repeated earthquake reached up to 30.1% to 40.6% higher than the single earthquake. Therefore, the behaviour factor, q from 2.3 to 5.5 is acceptable to be used for seismic design of new reinforced concrete moment resisting frame building on Soil Type B in medium seismic region in Malaysia. On Soil Type D, the behaviour factor, q is limited from 2.3 to 4.54.